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Assessing the Accuracy of a UAV Snow Depth Survey: Utqiagvik (Barrow), Alaska CALM Grid

Ian Nichols
Michigan Technological University, ionichol@mtu.edu

ASSESSING THE ACCURACY OF A UAV SNOW DEPTH SURVEY:
UTQIAGVIK (BARROW), ALASKA CALM GRID

By

Ian O. Nichols

A REPORT

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Department of Geological and Mining Engineering and Sciences

Report Co-Advisor:	*Dr. Kenneth M. Hinkel*
Report Co-Advisor:	*Dr. John S. Gierke*
Committee Member:	*Dr. Thomas Oommen*
Department Chair:	*Dr. John S. Gierke*

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I would like to thank my committee for their mentorship and help in producing this document. Thank you, Ken, for providing me with the opportunity to participate in the 2019 field campaigns, all the contributions and revisions to this report, and for always being available for any questions. Thank you, John, for initially introducing me to this project. Thank you, Thomas, for helping me improve my ArcMap skills over the past two years. Additionally, I would like to give a special thank you to Dr. Benjamin Jones, who was the pilot and data processor for all UAV surveys. This project would certainly not be possible without you, Ben.

This work was also largely made possible through collaboration with the Ukpeagvik Iñupiat Corporation (UIC) of Utqiagvik (Barrow). The UIC is for-profit Alaska Native village corporation that was founded under the Alaska Native Claims Act (ANCSA) of 1971. Iñupiat refers to the group of Alaska Natives whose original territories span across Alaska's north slope; northeast from the Bering Sea's Norton Sound to the northern most point of the Alaska/Canada border. This community (like other Inuit groups) descends from the historic Thule culture that emerged in coastal Alaska around 1000 BC. Over the centuries, the Iñupiat people have developed a very strong cultural and spiritual connection with their traditional lands, while heavily relying on them for communal subsistence hunting and fishing. Whaling is a common practice in coastal villages like Utqiagvik; where a single harvest provides each member of the community with valuable nutrition, which is particularly important in an environment with limited access to fruits and vegetables. As a result, many core Iñupiat cultural values revolve around their relationship with the land, and include hunting traditions, respect for wildlife, and the land of their sustenance (Iñupiat Cultural Values, ankn.uaf.edu). This compassion for land and animals also extends to their community as well, with other core values including respect for others, love for children, avoidance of conflict, and responsibility to tribe.

When the ANCSA was enacted, Alaska Native land claims were greatly reduced and the relationship between Iñupiat Alaska Natives and their land shifted largely from communal to corporate ownership. Alaska Natives received $944 million and ownership of 44 million acres in exchange for 340 million acres of traditional lands that were deemed oil rich. As a result, the Iñupiat people of Utqiagvik formed the UIC, with the

goal of developing their remaining resources while honoring centuries old cultural heritage. Today the UIC owns over 200,000 acres across Alaska's North Slope.

Since its founding, the UIC has developed into a very diverse corporation with business interests in almost all 50 U.S. States. The UIC operates a family of companies offering public services in construction, architecture/engineering, regulatory consulting, oil spill response, marine service, information technology, maintenance/manufacturing, and logistics for military and scientific exploration. The logistics services provided our research team with all safety training, snowmobiles, and housing required for our field work in Utqiagvik. The UIC's commitment to aiding in arctic research has been strong for decades, and in 1992 the Barrow Environmental Observatory was dedicated. This observatory encompasses 7,400 acres that are dedicated strictly to scientific research. Despite having influence across the entire U.S., the UIC is still dedicated to serving the people of Utqiagvik and offers services for local car rental/repair, hospitality, catering, facility maintenance, natural gas sales, and real estate management. Formerly known as Barrow, a 2016 community wide vote decided to rename the city to its traditional Iñupiat name of Utqiagvik.

Abstract

Active layer depth and snow depth are annually collected across the Circumpolar Active Layer Monitoring (CALM) Network to observe the response of the active layer and near-surface permafrost to climate change over decadal-time scales. Snow depth is typically measured using a graduated steel probe at each grid node but, in this paper, we explore the viability of using Unmanned Aerial Vehicle (UAV) (drone) technology to collect snow depth measurements at the 1 km^2 Utqiagvik (Barrow), Alaska CALM grid. This is achieved by comparing estimated UAV snow depths to measured snow depths collected using a MagnaProbe (MP) at each of the 121 grid node locations. It was found that the UAV shows an average snow depth about 7-cm shallower than that measured by the MP. Grid node locations with the most inaccurate UAV snow depths were concentrated in areas with standing water at the time of the summer UAV survey, and at the margins of the survey area.

1 Introduction and Purpose

In an effort to facilitate long-term collection of standardized measurements of the climate-permafrost system in polar and alpine regions, the Circumpolar Active Layer Monitoring (CALM) Network was established in 1991 under the auspices of the International Tundra Experiment. It has been continually supported by the U.S. National Science Foundation since 1998. The primary goal is to observe the response of the active layer (summer thaw zone above permafrost) and near-surface permafrost to climate change over decadal-time scales in representative terrain, using established protocols to collect observations that are suitable for inter-site comparison. The vast majority of sites observe soil temperatures and measure active-layer thickness on grids ranging from 1 ha to 1 km^2. Surveyed grid nodes are established at 10-m intervals on the 1-ha plots, and at 100-m intervals on the 1-km^2 sites, yielding 121 grid nodes at which observations of active layer depth, soil moisture, snow depth, vegetation, etc. are collected, typically at the end of the thaw season (August) and in late-winter (April). Most of the more than 200 sites in the CALM network are located in Arctic and Subarctic lowlands, with newer sites established in Antarctica and South America. Annual measurements are archived on the George Washington University web site (https://www2.gwu.edu/~calm/), which contains archived data sets, a table of summary statistics, a map of the sites, measurement protocols, CALM forms, equipment installation instructions, uploading and downloading instructions, and other pertinent information.

Warming temperatures in cold regions are expected to produce widespread, systematic changes in the thickness of the active layer. These changes will have many far-reaching effects, and the broader impacts of this project come from considering these impacts on the flux of greenhouse gases, on human infrastructure, and on landscape processes. Continued observational and analytical investigation over decadal time-scales is crucial for detecting long-term changes and assessing trends. If current trends of warming arctic temperatures continue, the thickness of the active layer will likely increase and cause a corresponding subsidence of the land surface that cannot be detected using depth measurements taken from the surface. To address this, part of the periodic data collection effort is directed toward the acquisition of accurate landscape elevation data. A more accurate understanding of the systematic changes in active layer thickness is possible by supplementing active layer probing measurements with Unmanned Aerial Vehicle (UAV) (drone) ground surface elevation data.

Typically, active layer depth and snow thickness are measured annually at each of the grid nodes using a graduated steel probe. Two measurements are made within 1 m of each grid stake, and the average is reported. Maps can be generated by spatially interpolating the discrete measurements across the study area. The process can be tedious, time consuming, and greatly under samples the site. A previous snow depth survey conducted along a snow fence near Barrow utilized a Differential Global Positioning System (DGPS) pulled behind a snow machine to address the limitations of manual surveys. Results showed that for a given area, automated snow depth surveys can achieve a much higher data resolution over the same duration of time, with similar accuracy

(Hinkel, Hurd. 2012). In this study, we assess the viability of using UAV technology to collect snow depth measurements. UAV surveys will benefit the CALM Network by improving the efficiency of annual data collection, and the overall quality of active layer and snow depth data sets.

Traditional manual measurement methods are cost-effective, use rugged/durable equipment, and produce highly accurate (though discrete) datasets. Because the process of manually recording snow depth takes considerable time, coupled with the harsh Arctic weather conditions, manually recording snow depths is a difficult task. Continued improvement and availability of UAV technology has raised the question of whether snow depth can be accurately measured using remote sensing techniques. Capturing snow depth with a UAV would drastically reduce the person hours required for a traditional CALM grid snow survey, while also allowing for a continuous snow depth data set for the entire study area at high spatial resolution. Recent attempts to produce high-resolution snow depth maps using UAV technology in the arctic have produced maps reaching a spatial resolution as high as 6 cm (Cimoli, et al. 2017). Unlike traditional manual methods, the general procedure for measuring snow depth with a UAV is quite fast and simple, but requires the ability to post-process the data using ground control points. Collecting UAV data in the summer and post-processing with GPS data on visible ground control points on the tundra surface is a viable option for well-located and constrained orthophotos and DEM products. In the winter, when ground control points are covered by snow, this post-processing method does not work. To combat the need for visible ground control points, we wanted to test a new technology in the rapidly evolving world of UAV-based science applications. Using a Phantom 4 Real-Time Kinematic (RTK) UAV, we acquired elevation data in both the summer and the winter, and post-processed the data using the fixed GPS base station located at the BARC facility in Barrow. This method relies solely on the UAV image locations and the fixed base station position. Ground control points are not needed for UAV surveys using this method, as the RTK UAV stores relevant information with each image that can be used for post-processing the data using the fixed GPS base station. By subtracting the DEM representing base conditions (no snow present) from the DEM representing the snow surface, the depth of snow is calculated. The snow depth is simply the difference between the two DEMs collected by the UAV surveys. In addition to the annual snow depth surface elevation, the summer ground surface elevation should be resurveyed annually as well. This would allow for a more accurate interpretation of summer active layer thickness measurements, and the ability to monitor annual variations in the datasets.

No matter the confidence in any survey utilizing remote sensing methods, ground truth data will always be required for an accuracy assessment. We will be comparing UAV surveyed snow depth data to manually recorded data from each grid node. The primary method for directly comparing the snow depth recorded by the UAV and the manually recorded snow depth is by calculating the residual snow depth at each grid node. Residual snow depth is defined as the difference between the observed snow depth and the UAV-survey estimated snow depth (manual measurement - UAV survey = residual). Low-residual snow depths indicate that the remote method (UAV survey) agrees with the manual method, which is taken to be the more accurate method, and show nearly equal results. Large residuals indicate that the UAV surveys inadequately observe snow depth. Some of the reasons for inconsistencies are identified and evaluated in this work.

2 Study Area

The study area for this project is directly east of the coastal village of Utqiagvik (Barrow), Alaska, on the Alaska North Slope (Figure 1). The terrain is flat, covered with tundra vegetation, and underlain by permafrost. Snow cover persists for 7-8 months of the year. The CALM grid consists of 121 nodes evenly spaced 100-m apart, across an area of 1 km^2. The area encompassed by the CALM grid provides a range of geomorphic features (Figure 2). The western portion features the eastern margin of a drained thermokarst lake basin, which is bordered by a beach ridge on the basin margin. The beach ridge causes snow to accumulate downwind as a drift in response to strong and persistent easterly winds, resulting in a deeper snowpack compared to the surrounding area. One grid node that lies directly within this drift was ignored in the analysis since the grid node survey stake was not visible during the manual snow depth survey. The UAV survey indicated a snow depth of 122 cm in this location. The southeastern portion of a drained lake basin is visible in the northeastern quadrant of the grid. This basin has a noticeably darker signature in the UAV-derived orthomosaic due to the presence of standing water within low-center ice-wedge polygons. Finally, part of Elson Lagoon is visible in the southeastern corner of the grid. The two grid nodes that lie directly within this lagoon were ignored in the study.

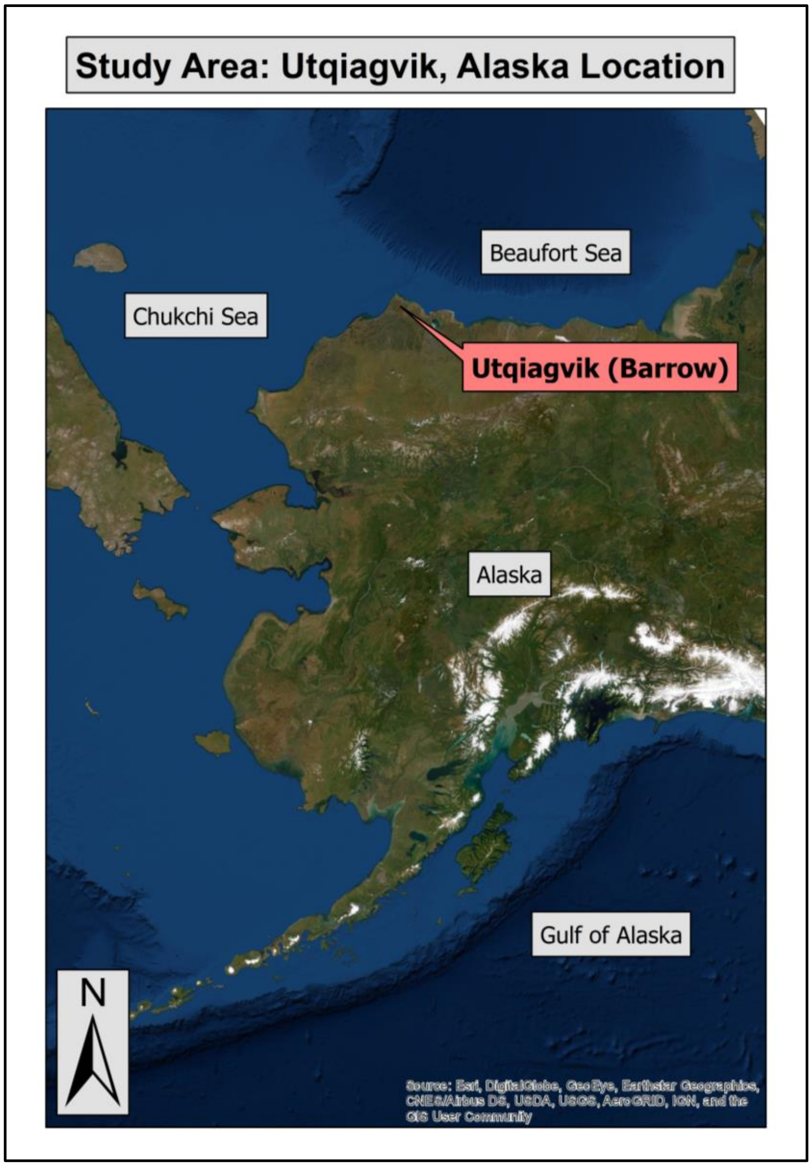

Figure 1: Location of Utqiagvik (Barrow) on the Alaskan North Slope (ESRI base-map).

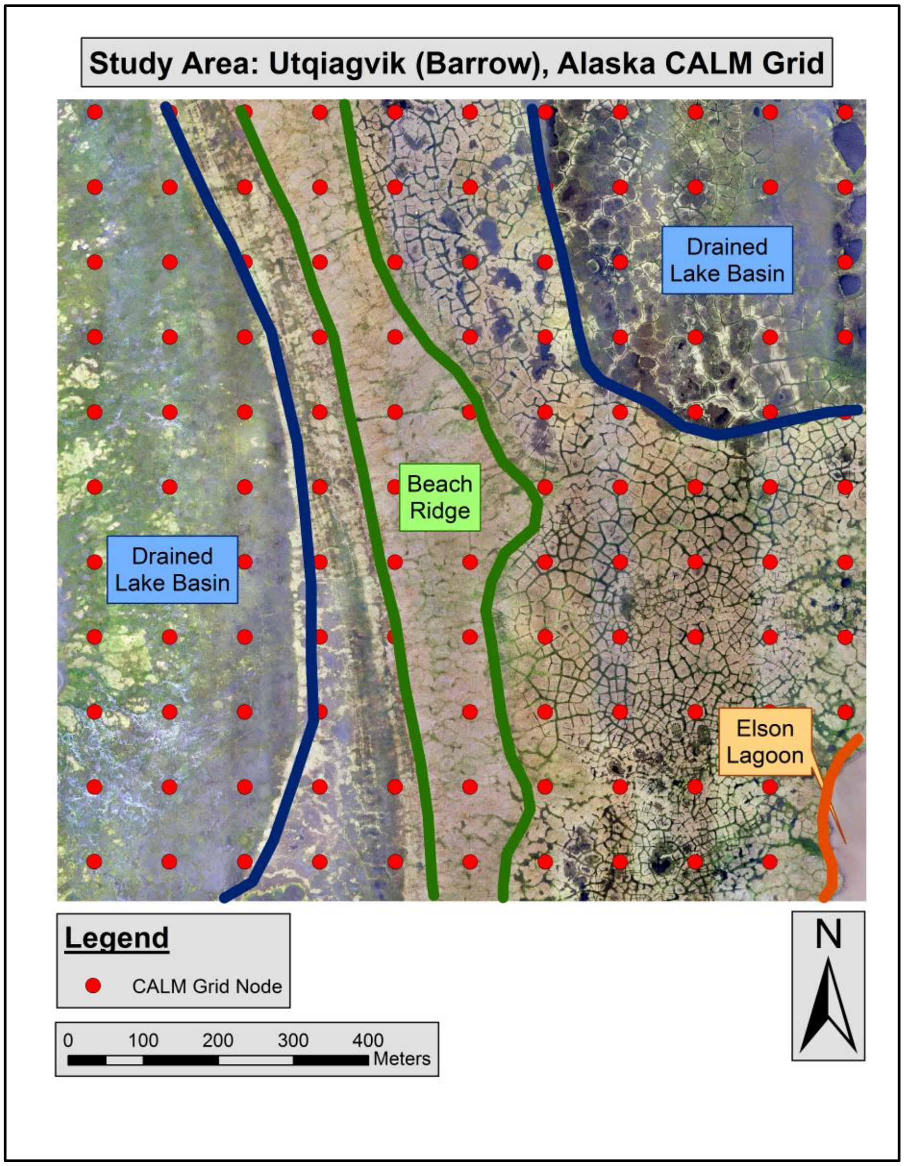

Figure 2: 4 August 2019 UAV-derived orthomosaic showing 118 CALM grid nodes utilized in the study. Drained lake basins are highlighted in blue, the beach ridge in green, and Elson Lagoon in orange.

3 Data and Methods

3.1 Data Collection

The snow surface DEM utilized in the survey was collected on 15 April 2019 during the winter field campaign, when the seasonal snowpack is generally considered to be at its maximum (Figure 3). This DEM represents the maximum elevation surface from which the base condition DEM will be subtracted. The base condition DEM represents the (snow free) summer ground surface and was collected on 4 August 2019 during the summer field campaign (Figure 4).

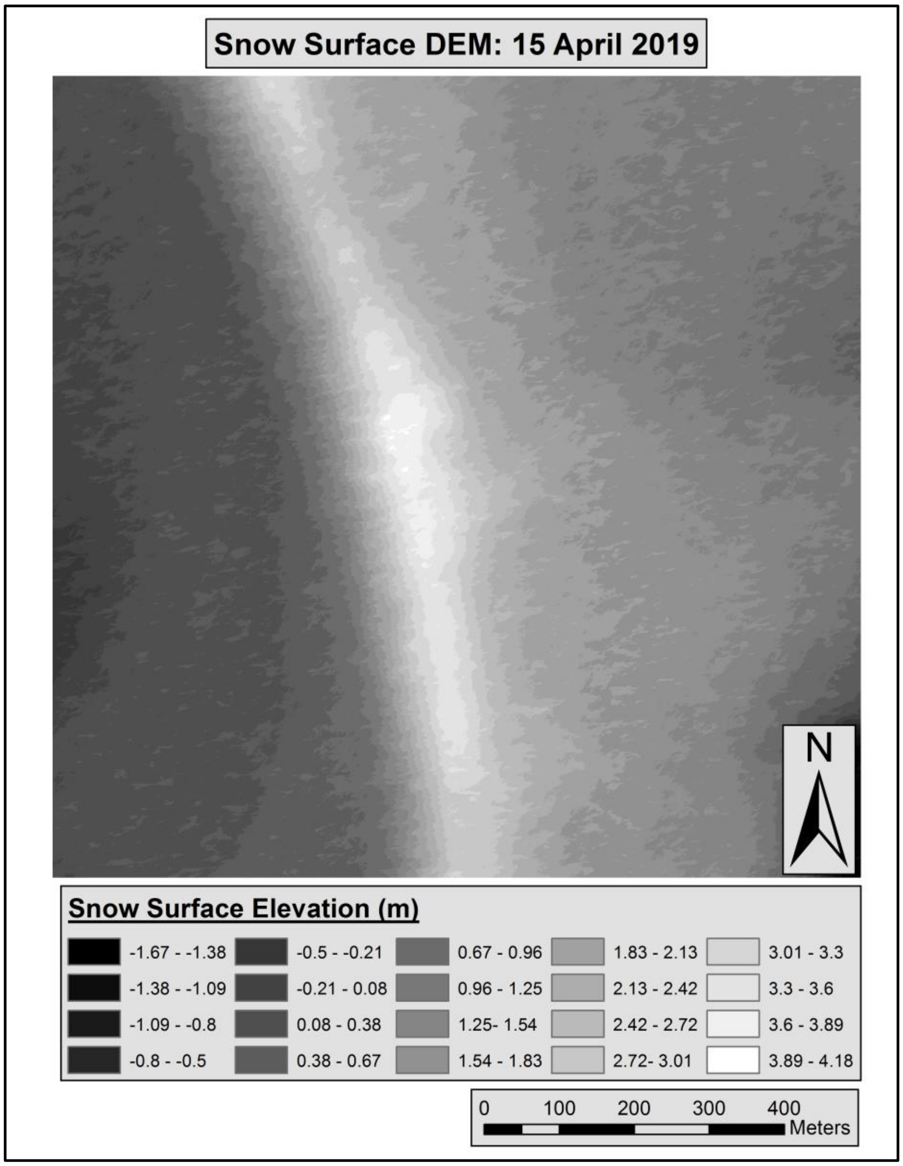

Figure 3: Snow surface DEM collected 15 April 2019. Elevations are relative to UAV base station. 25-cm spatial resolution.

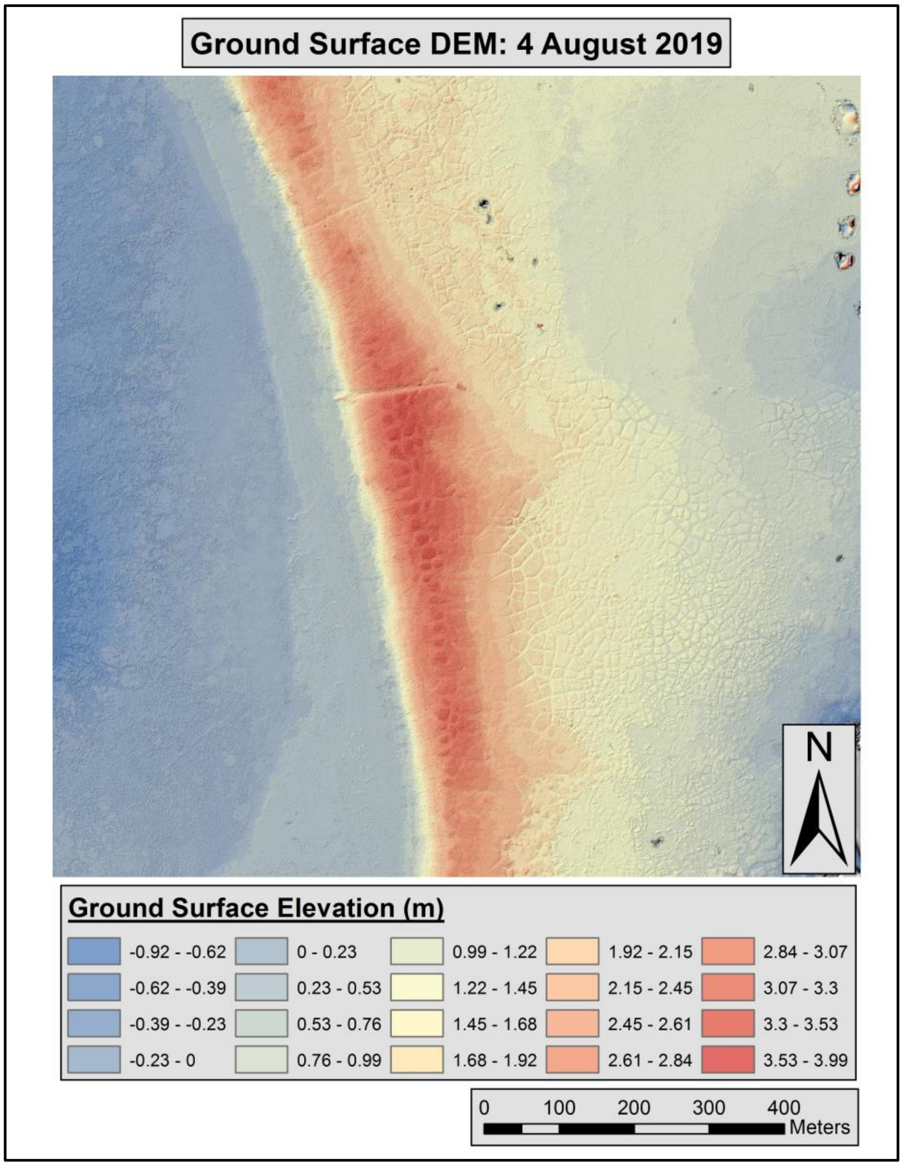

Figure 4: Hill-shaded (5x vertical exaggeration) ground surface DEM collected 4 August 2019. Elevations are relative to UAV base station. 25-cm spatial resolution.

Snow depth data were collected manually for ground truth assessment of the UAV data on 15 April 2019, after collection of the snow surface DEM. Confirmed snow depth measurements were required for assessing the accuracy of UAV estimated snow depth. The manual survey was performed using a MagnaProbe (MP) to make two snow depth measurements at each of the 118 viable nodes that comprise the CALM grid. The MP was chosen for this study because it provides a fast and convenient way of pairing snow depth measurements to a GPS location. This device is composed of two main parts: 1) The backpack, which contains a Campbell Scientific CR800 data logger, GARMIN™ GPS receiver, batteries, electronics, and controls and 2) a 153-cm long steel pole. The steel pole has a plastic handle and thumb switch attached at the top, and a plastic basket designed to float on the snow surface at the base. Each time the rod is fully inserted into the snow, the basket remains on top of the snow surface. When the thumb switch is pressed, a sonic pulse travels from a magnet on the basket to a receiver in the top of the rod. The electronics in the backpack then convert the travel time of this sonic pulse to a snow depth, while also recording a corresponding GPS location. Vertical accuracy of the MP is reported to be 0.3 cm for 50-cm-deep snow underlain by permafrost (Sturm, Holmgren. 2018). The MP allows for collecting accurate snow-depth measurements in rapid succession, as an individual measurement takes less than 2 seconds.

For this survey, one MP measurement was made approximately 1-m due north of each grid node, while the other was made ~1-m due south. When the survey was finished, the data were extracted to a spreadsheet file displaying the geographic coordinates and snow depth of each measurement location. The MP is a useful device for accelerating the process of manually surveying snow depth, but it has some intrinsic limitations. First, the MP can only measure snow depth to a maximum of 140 cm. Additionally, the MP's GPS has a spatial uncertainty of 3 m. This posed a problem for reliably comparing the UAV-collected snow depth data to manually-collected ground truth data, but a solution is described in the following paragraphs.

3.2 Estimating UAV Snow Depth

The inferred UAV-measured snow depth is calculated using two separate DEMs from two distinct surveys in different seasons, approximately 4 months apart. Data collection and processing was conducted by Dr. Benjamin Jones from the University of Alaska-Fairbanks. The top of the winter snow surface was surveyed on 15 April 2019 and the summer ground surface on 4 August 2019. All images were collected with a Phantom 4 UAV (P4RTK) and post-processed/georeferenced to NAD83 Zone 4 North in Ellipsoid heights using a propeller aeropoint and Pix4D (version 4.3.33 for April survey, 4.4.12 for August). A spatial resolution of 25 cm was selected during post-processing, as this achieved a good balance of resolution and file size. DEM creation was done in Quick Terrain Modeler (QTM) with the densified point cloud from Pix4D. The vertical accuracy of the dataset is a product of the structure-for-motion (SfM) software. Vertical accuracy for the April survey was 18 cm and 10 cm for the August survey.

Once the files were properly oriented, formatted, and imported to ArcMap, the summer ground surface DEM was subtracted from the snow surface DEM using the "Raster Math" tool within ArcMap. The output raster file is composed of elevation values representing snow depth (Figure 5).

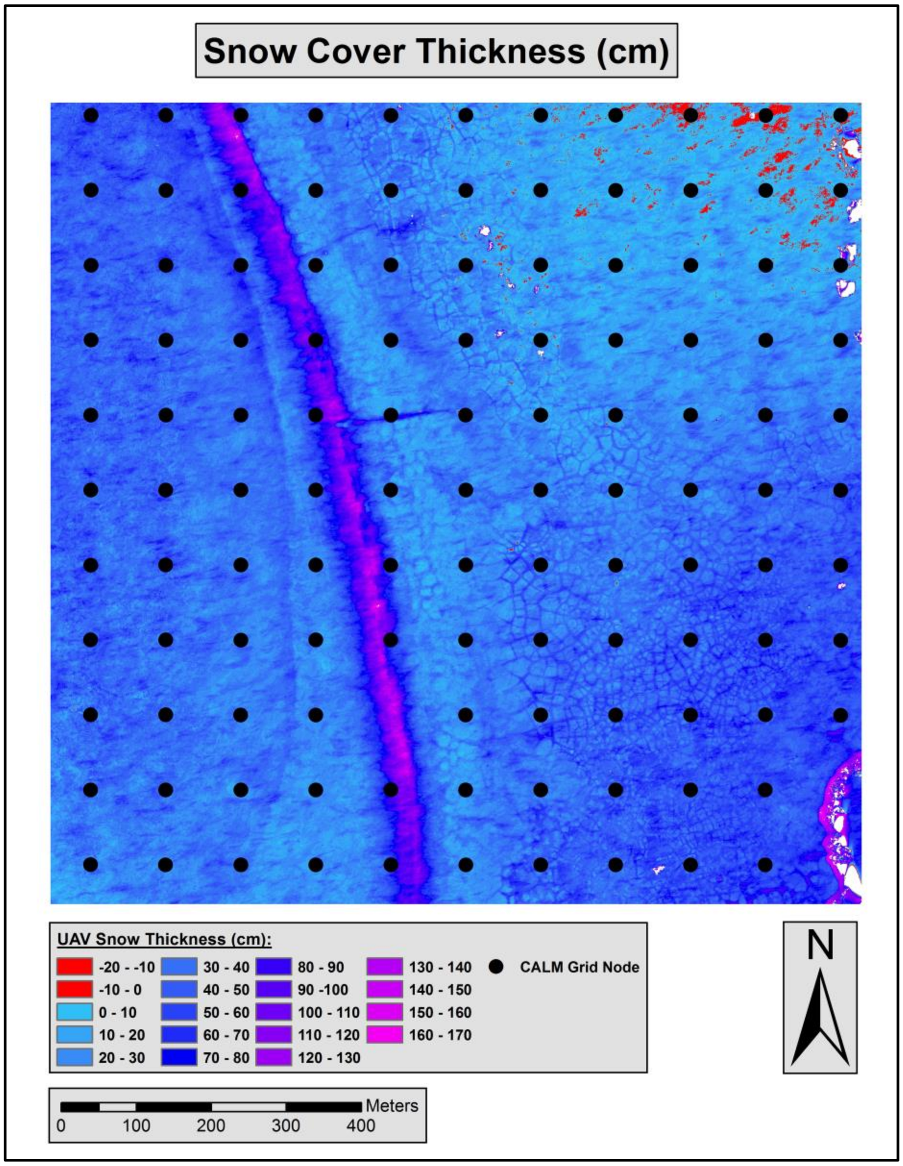

Figure 5: 15 April 2019 UAV snow depth survey results with 25-cm spatial resolution (processed and created by Dr. Ben Jones, University of Alaska-Fairbanks).

3.3 Survey Method Comparison

To compare the different snow-depth measurement approaches, it was required that the UAV snow measurement and MP snow measurements were compared at co-located spatial points. The MP measurements were made approximately 1-m due north and 1-m due south of the grid node survey stake. However, the 3-m spatial uncertainty associated with the MP internal GPS caused these measurement locations to be randomly placed within a 3-m halo surrounding their true location when mapped in ArcMap. It was assumed that the northernmost mapped MP measurement location corresponds to the MP measurement made 1-m north of the survey stake, and the southernmost corresponds to the measurement made 1-m south of the survey stake. Once matching the MP snow depth values with their respective locations, the UAV-measured snow depth at the same location could be assessed.

During the MP survey from April 2019, the measurement distances of 1-m north and 1-m south of the survey stake were visually estimated to use time as efficiently as possible. To account for this uncertainty, UAV surveyed snow depth data was considered within a range of 0.75 – 1.25 m to the north and south of each survey stake. This was achieved by averaging the estimated snow depth in the 4th and 5th pixels to the north and south of the pixel containing the survey stake (pixel size of 25 cm). The average of the 4th and 5th pixels to the north of the survey stake should correspond to the location of the northernmost MP measurement, and the same holds true for the measurement made approximately 1-m due south of the stake. Once this averaging was completed for all 118 valid grid nodes, it was possible to conduct a meaningful comparison of the two data sets.

The variability within each dataset was considered before comparing the methods. This was done by calculating and examining the general snow depth statistics from each survey, as well as calculating and mapping the "Difference Percentage" (DP) at each grid node. The DP is defined as the range between the two snow depth measurements made at a grid node, divided by the mean snow depth at that location, and expressed as a percent. An example is outlined below:

Measurement 1: 40.9 cm	DP = (Range/Mean) x 100%
Measurement 2: 42.1 cm	DP = (1.2/41.5) x 100%
Mean: 41.5 cm	**DP = 2.8%**
Range: 1.2 cm	

The DP is intended to quantify the variability between a pair of grid node measurements, separated by ~ 2 m. A low DP indicates that the range between each measurement is low relative to the mean snow depth, while a high DP indicates that the range is high and there is considerable variability between measurements at that location. These values were calculated and mapped to assess spatial patterns (Figure 6). The same operation was performed for the UAV pairs at each grid node (Figure 8).

The two surveying techniques were compared by calculating the residual snow depth between each data set. The residual snow depth is defined as the difference between the observed snow depth (average of MP pair) and the inferred snow depth (average of UAV-derived pair) as illustrated in the example below:

Average MP (observed): 41.5 cm	Residual = Average MP – Average UAV
Average UAV (expected): 47.1 cm	**Residual** = 41.5 – 47.1 **= -5.6 cm**

Negative values of residual snow depth, like the example above, indicate that the estimated snow depth derived from the UAV surveys is greater than the observed snow depth measured with the MP. A positive residual means the observed depth is greater than the depth inferred from the automated UAV survey. Ideally, the residual snow depth would be zero, indicating that both forms of measurement calculated an identical average snow depth at that grid node location. Mapping the residual snow depths could show spatial patterns that might suggest causes for inconsistencies in the remotely sensed data.

4 Results and Discussion

4.1 MagnaProbe Survey Snow Depth Values

There were 236 MP snow depth measurements collected to serve as ground truth data for the study. A *t*-test indicates there is no significant difference in the mean between MP-1 and MP-2 (only 1.1 cm of difference, Table 1). The standard deviation, minimum, and maximum snow depth values all show little difference, as well. This result is expected since the measurements were collected less than 2-m apart. The MP dataset will serve as a basis to which the UAV values are compared.

Table 1: Summary statistics for MagnaProbe (MP) measurements. It is important to note that MP-1 & MP-2 do not correspond to a northern or southern direction of measurement.

	n	Mean (cm)	Std. Dev	Min	Max
MP-1	118	42.2	13.9	15.2	99.9
MP-2	118	43.3	14.9	15.9	101.5

The MP DP was plotted at each grid node to assess any spatial patterns in the variability of the manual snow depth measurements (Figure 6). Larger circles were used to symbolize a greater difference between the two measurements. The lack of any spatial pattern regarding the larger inconsistencies indicates variation within the data is most likely due to micro-relief of the snow (*sastrugi*, Figure 7) and ground surface. A more consistently large DP can be observed in the eastern portion of the CALM grid. This likely results from increased micro-topography of the ground surface associated with well-developed ice wedge polygons. This exercise demonstrates the intrinsically high spatial variability of the snow cover thickness, even over the short (2-m) distances separating the paired measurements.

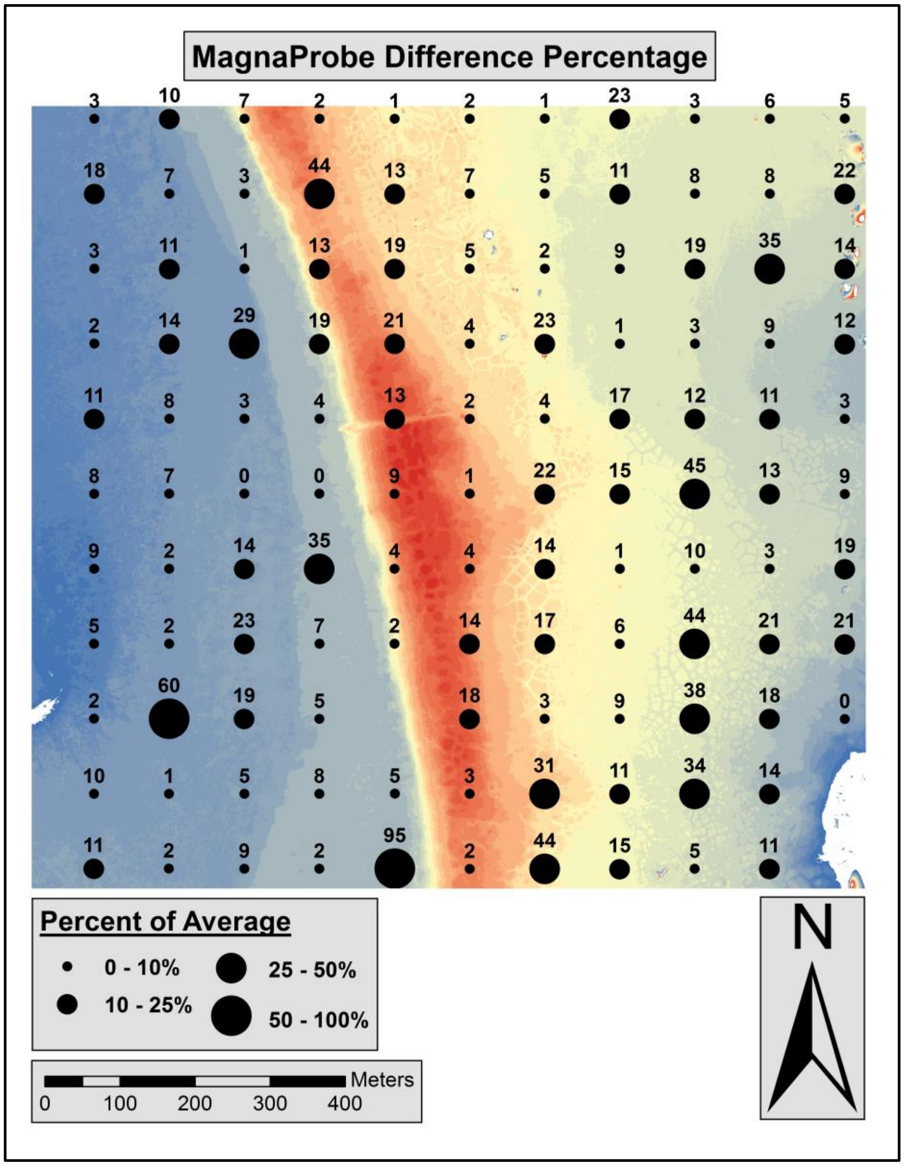

Figure 6: MagnaProbe difference percentage (DP) overlaying ground surface DEM from summer 2019 UAV survey.

Figure 7: Highly wind-sculpted "sastrugi" snow surface. Snowmobile for scale.

4.2 UAV Survey Snow Depth Values

There were 236 UAV-estimated snow depth values considered in the analysis. Summary statistics for the paired measurements are shown in Table 2. Note that the difference between the mean of paired UAV measurements was only 0.7 cm. Note also that, compared to the paired MP measurements (Table 1), the mean snow thickness of the UAV estimates is about 7-cm smaller while the standard deviation is several cm greater. The UAV survey recorded negative snow depths at some locations, and this could have occurred in two ways: 1) Error introduced by the limitations of the vertical accuracy of the UAV survey such that estimated snow depth exceeds the recorded snow depth, and/or 2) summer ground surface elevation was greater than the winter ground surface elevation. The latter could be caused by the presence of standing water during the summer UAV survey and will be discussed in detail in the next section.

Table 2: Summary statistics for UAV survey measurements.

	N	Mean	Std. Dev	Min	Max
UAV-N	118	34.9	17.1	-0.8	93.3
UAV-S	118	35.6	19.1	-7.8	107.4

The map showing UAV DP values shows a random distribution of paired measurements with a high level of spatial variability (Figure 8). This can once again be attributed to the high level of micro-topography of the snow and ground surface. Some DP values fall outside the range of 0-100%, as the average UAV snow depth values in these locations were negative. Grid nodes where estimated snow depth was less than zero and the DP value was voided are symbolized on the map with a black "X" inside a white square. These instances were limited to the drained lake basin in the northeastern quadrant of the map area, where the edge of the survey area also results in a lower number of overlapping UAV photos for DEM construction. A systematic increase in the variability of UAV snow depth estimates can be visualized by the increased number of larger sized white circles.

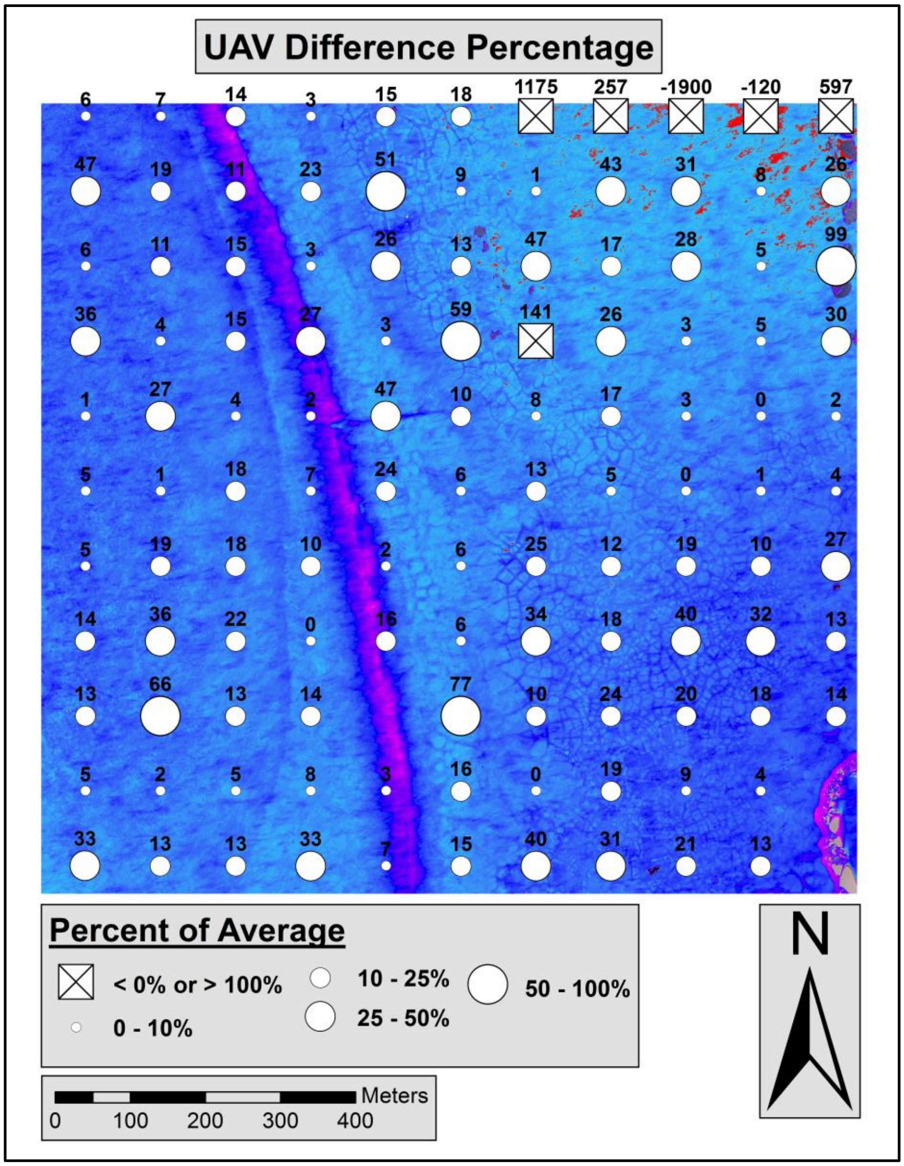

Figure 8: UAV difference percentage (DP) value for each of the 118 grid nodes considered underlain by UAV snow thickness.

4.3 Means of Paired Measurements

The comparison of survey methods was done by considering the mean snow depth at each grid node for each survey method. There is a considerable difference between the expected and confirmed mean snow depths over the entire study area, with the UAV survey method showing an average snow depth over 7-cm shallower than that measured by the MP (Table 3). The minimum UAV snow depth value is also 16.5-cm shallower than the minimum MP value. This significant difference largely results from the negative snow depths recorded by the UAV in the northeastern portion of the grid area. The 2019 UAV snow depth survey is a slight improvement over recent attempts to measure snow depth using a UAV (Harder, et al. 2016; Bühler, et al. 2016). Root mean square errors in UAV snow depth estimates from these studies have ranged from 8.5 – 15 cm.

Table 3: Summary statistics for the mean of paired measurements.

	N	Mean	Std. Dev	Min	Max
MP	118	42.8	13.8	16.2	97.4
UAV	118	35.2	17.6	-0.3	94.8

The mean snow depth from each survey is shown in Figure 9, which depicts the means overlying the snow depth map produced by the UAV survey. The beach ridge and its relatively deep snowpack on the lee side is clearly visible passing through the center of the grid area. Visible also at a finer scale is the impact of ice-wedge troughs, where snow depth can be several decimeters deeper; this pattern is especially apparent in the southeastern quadrant. Negative UAV measured snow depths (red) are also scattered across the northeastern portion of the grid area.

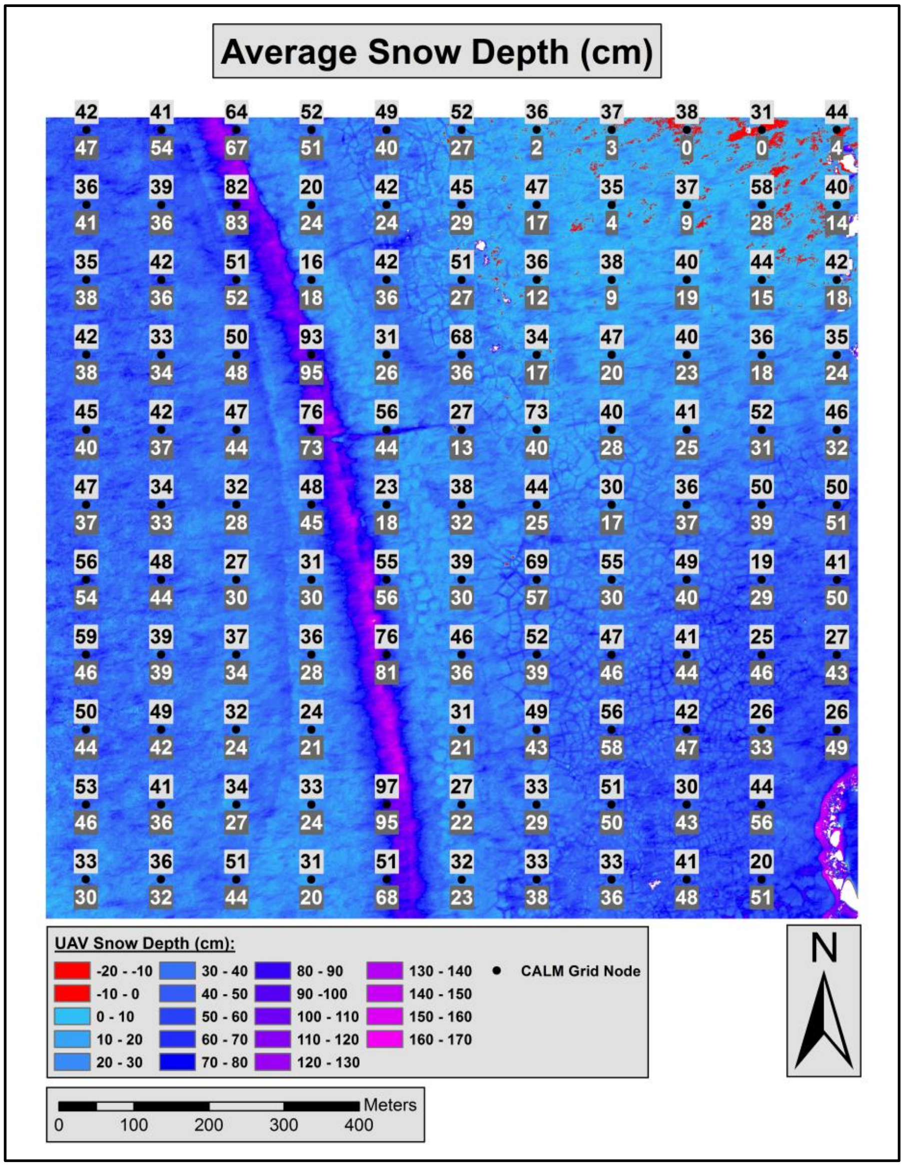

Figure 9: Average snow depth values at each of the 118 CALM grid nodes on 15 April 2019. Values measured with MagnaProbe are in black text, while values extrapolated from UAV are in white text.

4.4 Residual Snow Depth

Once the mean of the paired snow measurements was determined for each survey method at each grid node, it became possible to directly compare the results of each survey by calculating the residual snow depth. As mentioned previously, the residual snow depth is the mean expected (UAV measured) snow depth subtracted from the mean observed (MP) snow depth. Positive residuals indicate that actual snow depth was deeper than that estimated by the UAV as shown in blue on the maps (Figure 10 & 11). Conversely, negative residuals (displayed in red), indicate that the actual snow depth was shallower than the depth estimated by the UAV.

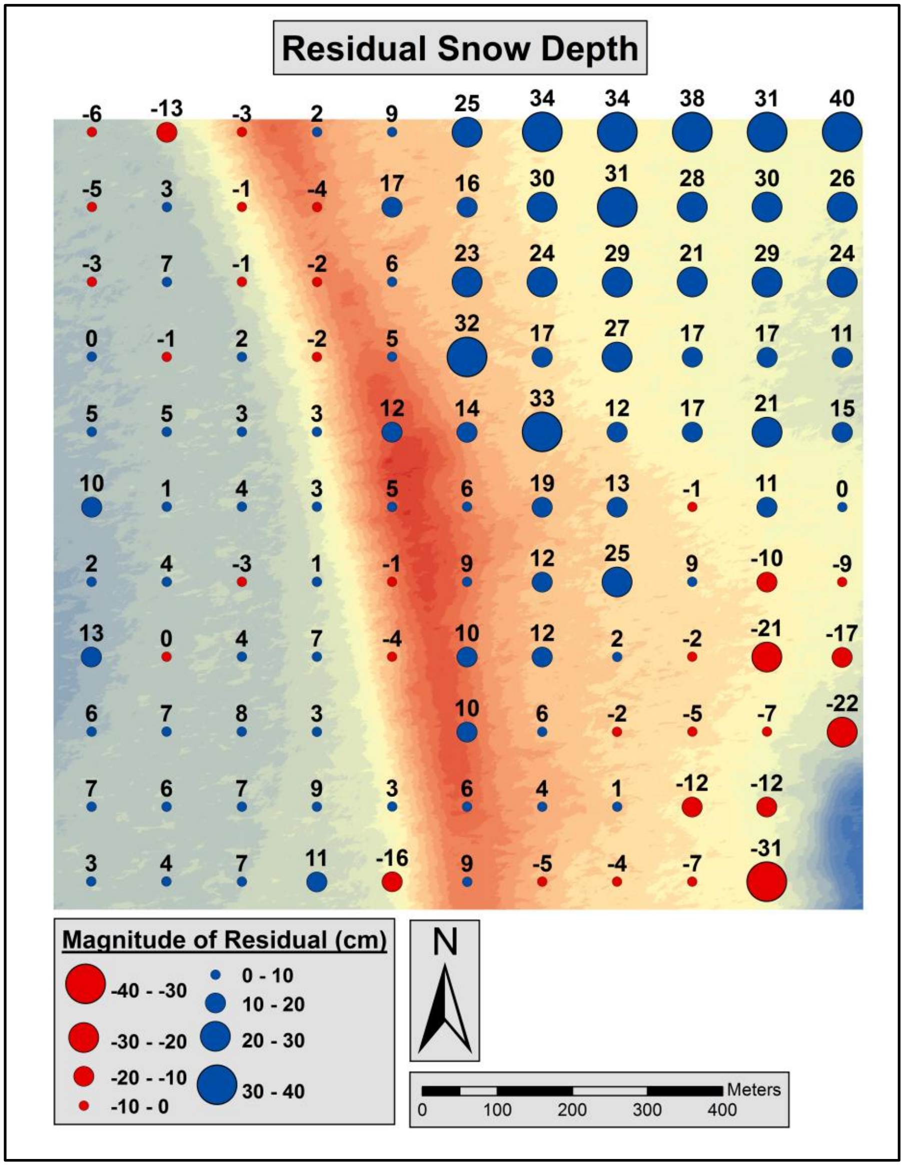

Figure 10: Residual snow depths ((observed - expected), in cm) overlaying snow surface DEM collected by UAV on 15 April 2019.

Spatial patterns of residual snow depths are apparent across the CALM grid (Figure 10). While positive residual values are prevalent across most of the survey area, the largest magnitude positive residuals are concentrated in the northeastern quadrant of the grid. Some of these residuals are extremely high (>40 cm), indicating a significant discrepancy with the results of the UAV survey in this location. The map underlain by the orthomosaic image shows that these grid nodes are primarily located in the very wet drained lake basin (Figure 11). The large positive residuals in this area could be attributed to the very wet conditions that affected the area in the summer of 2019, when the base condition DEM was collected (Table 4). A total of 80 mm of rain fell in June and July, prior to the collection of the ground elevation on 4 August. Typically, only 33 mm fall during this period. Excessive surface water ponded above the permafrost would artificially inflate the ground surface. This results in a decrease in the estimated snow depth, and/or causes error in the development of the DEMs using the SfM technique. Meteoric water would tend to persist in poorly drained lake basins. However, 20 – 40 cm of standing water seems excessive, and other sources of UAV survey inaccuracies should be investigated.

Further analysis of the residual snow depth map reveals that there are a few large negative residual values in the southeastern corner of the grid. This is an area of significant microtopographic variation due to the presence of ice-wedge polygons which may increase spatial variability. There could be a relation between the lagoon margin and the negative residual values and a closer inspection of this area should be considered.

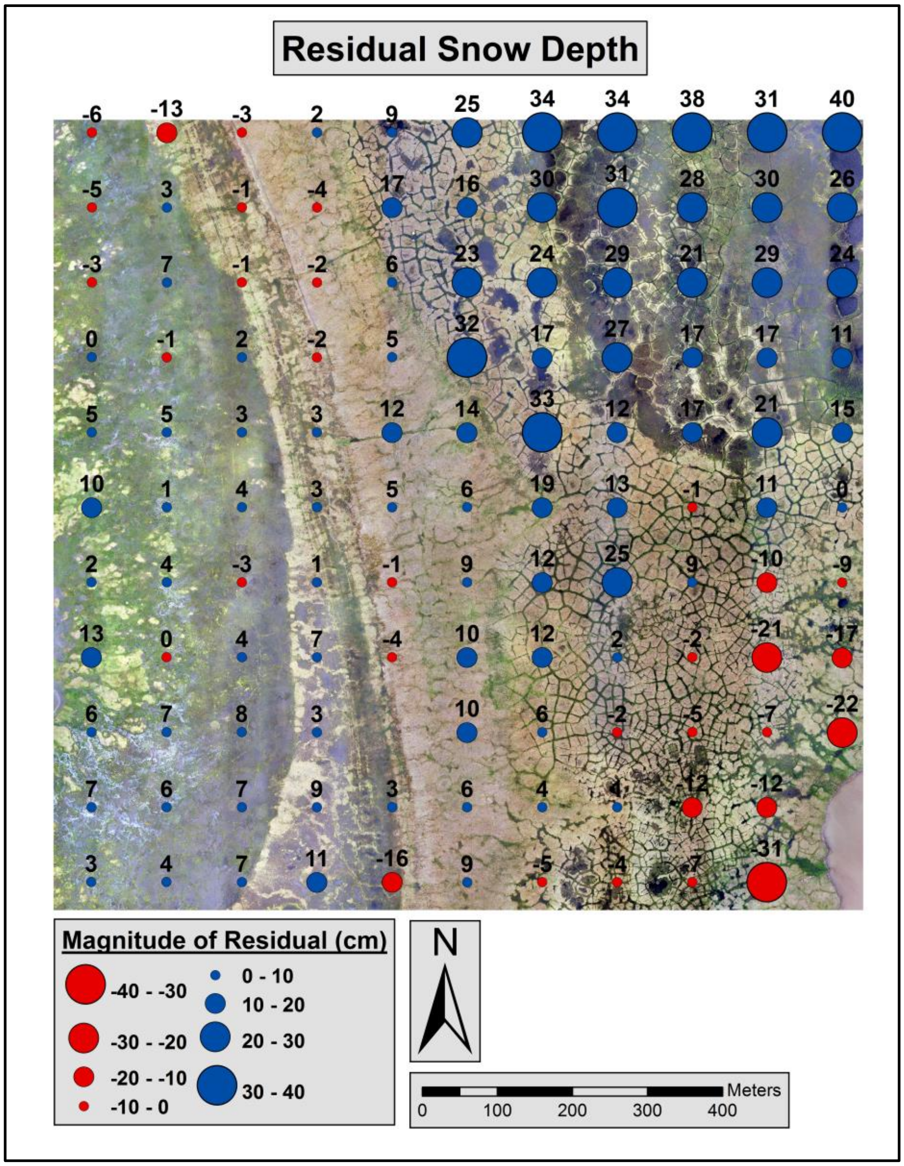

Figure 11: Residual snow depths overlaying 10-cm orthomosaic imagery collected on 4 August 2019.

Table 4: Precipitation data (mm) highlighting the abnormally wet summer of 2019 that affected the study area.

Month	1981-2010 (Normal)	2019	Difference from Normal
June	8.1	23.9	15.8
July	24.9	56.1	31.2
August	26.7	57.9	31.2
Sept	18.3	23.4	5.1

4.5 All Snow Depth Measurements

An analysis of all the measurements from each survey shows the full range of snow depth values recorded in the study. There is a substantial difference in the minimum snow depths with the UAV survey estimating negative values in some locations (Table 5). However, the maximum snow depth value was also recorded by the UAV. The larger range of snow depths associated with the UAV survey method is reflected by the higher standard deviation in its measurements, relative to the MP values. The tendency for the UAV to record shallower (and even negative) snow depths creates a considerable difference in the mean snow depth, as well. However, the ability of the UAV to record snow depths >140 cm would be beneficial in areas with extremely thick snowpack.

When ice-saturated ground thaws, it will also subside as ice is converted to water. By assuming 50% soil porosity, a thaw depth of 40 cm, and a phase-change volumetric reduction of 10%, we estimate 2 cm of seasonal ground surface subsidence by the end of summer. The effect from this would be to overestimate UAV snow depth estimates by this amount. Additionally, water covered surfaces that freeze could increase the elevation of the winter snow surface. Thus, the difference between the MP and UAV methods may average as much as 9+ cm.

Table 5: Summary statistics from all snow depth values considered in the study.

	n	Mean	Std. Dev	Min	Max
All MP	236	42.8	14.1	15.2	101.5
All UAV	236	35.2	18.1	-7.8	107.4

Analyzing the snow depth measurements from each survey technique reveals the advantages and limitations associated with each method. The MP survey provided a quick and efficient way to capture accurate snow depth measurements and GPS location at each grid node. The 100-m spacing between each grid node makes conducting a MP survey of the entire CALM grid a time-consuming endeavor. The 3-m spatial uncertainty associated with the MP internal GPS also makes accurately correlating confirmed snow depth values to expected UAV snow depth values a primary limitation of the study. More accurate co-location of snow depth measurement values from each survey method would greatly improve the quality of the UAV survey accuracy assessment. Results from the UAV survey offer an advantage to the MP survey by providing a continuous snow depth surface across the entire grid area, which improves our understanding of snow distribution over the entire grid area when compared to the sparse collection of manual snow depths at individual grid nodes. However, there is still too much uncertainty with the UAV survey. Inaccuracies associated with high summer water levels and low data resolution at survey boundaries must be resolved before the UAV can be considered a primary instrument for snow depth surveys.

5 Conclusions

For the past 25 years, the CALM Network has provided climate scientists with the data necessary for understanding how the Earth's cryosphere is responding to climate change. The main goal of the CALM program is to gather data on the active layer above permafrost to improve our understanding of how the flux of greenhouse gasses through the permafrost changes over time. Part of this data collection effort is composed of annual snow depth measurements collected during the winter. A standard snow survey involves sampling each of the grids' 121 nodes for snow depth using a steel probe. The paired mean of two snow depth values represents the snow depth for an individual grid node. This process is tedious and can take several hours to complete. Manual measurements also under-samples the grid area. This study assessed the accuracy of a snow depth survey that utilizes remotely sensed UAV-derived DEMs to calculate snow depth measurements.

The process of calculating snow depths consists of subtracting a ground surface DEM prior to snowfall from a snow surface DEM, both of which can be derived from UAV surveys. The snow surface DEM was collected on 15 April 2019 with 18-cm vertical accuracy, while the ground surface DEM was collected 4 August 2019 with 10-cm vertical accuracy. The UAV surveys capture the general distribution of snow across the grid and show detail such as deeper snow in ice-wedge polygon troughs.

Ground truth data was collected using a MagnaProbe (MP) immediately after the UAV flew over the grid in April 2019. This dataset provided 236 confirmed snow depth values (0.3-cm vertical accuracy) that were co-located with estimated snow depth values from the UAV survey at matching spatial locations. The random distribution of difference percentage (DP) values for the MP survey is reflective of the intense microtopography of the snow and ground surface. The UAV survey shows a similarly random distribution of DP values. This highlights the UAV survey's ability to capture small variations in snow depth, even at distances of less than 2 m. However, the UAV survey estimated snow depths that were, on average, 7.6-cm shallower than observed measurements. This difference is largely skewed by the presence of negative UAV snow depth values in the northeastern quadrant of the grid. Many grid nodes in this area reported UAV snow depths around 30-cm shallower than the observed snow depth.

The primary reason for under estimating snow depth in the northeastern quadrant of the grid is that this area was much wetter than the rest of the study area in summer 2019. The drained lake basin that extends into this area of the grid was submerged in water. When standing water is present at the time of the summer UAV survey, the baseline ground elevation will be overestimated (and highly inaccurate) due to noise getting introduced to the SfM algorithm. The UAV could considerably underestimate the snow depth if enough water was present. However, the 30 – 40-cm residual snow depths seem too high for this to be the only source of error in the data.

Another source of error could come from the MP's style of measurement. The float (~30 cm in diameter) that remains on top of the snow surface as the MP is inserted into the snow rests on top of the highest point of relief on the highly wind-sculpted snow surface. In some cases, this could cause the snow depth to be over-sampled by the MP by a range of 5 – 10 cm.

Comparing the UAV surveyed snow depth data to the data collected with the MP shows that transitioning to remote methods for CALM grid snow surveys is becoming a viable option. The ability to produce a continuous raster file containing snow depth values at 25 cm or finer spatial resolution in a relatively short amount of time would be beneficial to scientists conducting any research where regional snow depth would be desired. In this study, we identified that the increased presence of surface water during the summer UAV survey was a key source of inaccuracy in the UAV data. To address this issue, a preliminary investigation should be conducted before the summer UAV survey with the goal of identifying areas with considerable amounts of standing water. This water depth should be recorded and incorporated into post-processing of UAV survey imagery. This would give a more accurate representation of the ground-surface surface elevation. Once this issue is resolved, it will become more possible to identify any systematic inaccuracies in the data. These types of inaccuracies are inherent to the method of measurement chosen for a given survey. They could be addressed by multiplying all UAV snow depth values by a type of coefficient to make them more comparable to the manually collected snow depth measurements. Additionally, vertical accuracy of UAV estimated snow depth is controlled by the vertical accuracy of UAV derived DEMs. The accuracy of UAV elevation data will likely increase as technology improves, but ground truth data will always be needed for assessing the accuracy of remotely sensed data. I recommend that the above points are addressed if a UAV survey of snow depth is repeated in future field campaigns. If the inaccuracies are reduced, the prospect of remotely sensing snow depth will become even more realistic.

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